Title

Global reconstruction of 20th century lake surface water temperature reveals different warming trends depending on the climatic zone

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Abstract

Lake surface water temperatures (LSWTs) are sensitive to climate change, but previous studies have typically focused on temperatures from only the last few decades. Thus, while there is good appreciation of LSWT warming in recent decades, our understanding of longer-term temperature change is comparatively limited. In this study, we use a mechanistically based open-source model (*air2water*), driven by air temperature from a state-of-the-art global atmospheric reanalysis (ERA-20C) and calibrated with satellite-derived LSWT observations (ARC-Lake v3), to investigate the long-term change in LSWT worldwide. The predictive ability of the model is tested across 606 lakes, with ninety-one percent of the lakes showing a daily Root Mean Square Error smaller than 1.5 °C. Model performance was better at mid-latitudes and decreased toward the equator. The results illustrated highly variable mean annual LSWT trends during the 20th century and across climatic regions. Substantial warming is evident after ~1980 and the most responsive lakes to climate change are located in the temperate regions.

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Introduction

Global climate change is increasingly evident from a wide variety of observations (Hulme 2016; Roe et al. 2017; Rogora et al. 2018). Surface air temperature measurements show a rapid increase in global temperature during the 20th century (IPCC 2013), and climate models project continued warming in the future (Cubasch et al. 2001; Meehl et al. 2007). Numerous studies have also shown widespread increases in lake surface water temperature (LSWT) (Schneider and Hook 2010; O'Reilly et al. 2015; Woolway et al. 2017a; Ptak et al. 2018). Such increases are of great importance to aquatic ecology, as changes in lake temperature influence a myriad of physical and ecological processes, including mixing patterns, phenology, and the structure of biotic communities (Adrian et al. 2009; Kraemer et al. 2015; Piccolroaz et al. 2015; Thackeray et al. 2016). Understanding lake thermal responses to climate is therefore critical for predicting biotic change and for anticipating the repercussions of climatic variability on lakes and their associated ecosystems.

While there is sufficient evidence to demonstrate that lakes have warmed in recent decades, our understanding of longer-term temperature change (e.g., extending back before the second half of the 20th Century) is comparatively limited. Global LSWT studies have relied heavily on thermal infrared imagery from spaceborne satellites and, as such, are restricted to the period since the early 1980's (Schneider and Hook 2010; O'Reilly et al. 2015). Other observational methods include paleolimnological temperature proxies (Tierney et al. 2010; Lehnherr et al. 2018) and in-situ measurements (Verburg et al. 2003; Austin and Colman 2008; Kainz et al. 2017; Woolway et al. 2017a; Matulla et al. 2018). However, the lakes investigated using these methods are relatively few in number. The lack of a global 20th century baseline temperature against which recent lake warming can be referenced limits quantitative understanding of LSWT trends observed in recent decades within the context of longer-term variability. For example, several lakes around the world have demonstrated a response to the recent warming 'hiatus' (1998-2012) (Medhaug et al., 2017), and LSWT trends evaluated during the hiatus period may underestimate longer-term warming (Winslow et al. 2018). In addition, analysing the relationship between large-scale teleconnection patterns and fluctuations of LSWT trends found in some regions (Livingstone and Dokulil, 2001; Blenckner et al. 2007; Katz et al., 2011; Salmaso 2012; Ptak et al. 2018) may provide new insights if a long-term global map of LSWT dynamics would be available. The extent to which lake warming has occurred at a global scale during the last century, and how those patterns vary across lakes worldwide, requires further investigation.

Due to the scarcity of in-situ observations, quantifying LSWT change worldwide during the 20th century requires a modelling approach. Trying to make reliable predictions of how LSWT has evolved due to climatic change is difficult. LSWT responds to complex thermodynamic fluxes (Henderson-Sellers 1986; Woolway et al. 2015), hence its precise quantification using process-based numerical models requires detailed over-lake meteorological data (e.g., wind speed, humidity, cloud cover) as inputs (Bruce et al. 2018). In-situ meteorological information of such fine detail is not frequently available above lakes worldwide and over long-time periods and meteorological gridded products are typically associated with coarse spatial resolution and larger uncertainties when extending back prior to the second half of the 20th Century. To overcome this limitation, previous studies have used simple regressive/statistical models (Webb 1974; McCombie 1959; Sharma et al. 2008).

These require as input only air temperature, a variable that is more often available and commonly more reliable than other meteorological variables (Gleckler et al. 2008). However, regression models are typically not able to address some fundamental physics and their use is controversial when applied with air temperature ranges beyond the limits of the time series used for model calibration (Piccolroaz et al., 2018), as would be expected under climate change.

To overcome the limitations of the aforementioned traditional modelling approaches, Piccolroaz et al. (2013) developed the *air2water* model, a hybrid model (Toffolon and Piccolroaz 2015) which combines a physically based derivation of the governing lake thermodynamic equations with a statistical calibration of model parameters. The model was developed to retain the simplicity of regression models, such as the limited number of required input variables, while preserving the robustness of deterministic models. *air2water* has been shown to provide similar performance, in terms of simulating LSWT, to process-based models (Toffolon et al. 2014; Piccolroaz 2016), and to be an effective tool to investigate LSWT responses to historic and future climate change (Piccolroaz et al. 2015; Piccolroaz et al. 2016; Wood et al. 2016; Czernecki and Ptak 2018; Piccolroaz et al. 2018; Piccolroaz and Toffolon 2018) also when applied to lakes with different morphological characteristics from around the world (Toffolon et al. 2014; Prats and Danis 2019).

Producing reliable projections of LSWT using only air temperature globally would be a major advantage for many scientific purposes and practical applications. For this reason, in this contribution we use *air2water* forced by a state-of-the-art global air temperature reanalysis product (ERA-20C) to simulate long-term LSWT change in 606 lakes worldwide during the 20th century. Besides showing the potential of this model for global-scale climate change impact studies on lakes, we use the reconstructed LSWT time series to investigate how lakes situated across climatic gradients have responded to climate change since 1900. Also, while previous studies have focussed on LSWT variations during summer (Jul-Sep) (Austin and Colman 2007; Schneider and Hook 2010; O'Reilly et al. 2015) we focus, in this study, on annually-averaged LSWTs, thus gaining a different, and potentially more insightful, perspective of LSWT change. With this study we aim at contributing to research on the lake thermal dynamics and trends through providing the first global reconstruction of LSWT during the 20th century.

2. Materials and methods

2. 1. Study sites and characteristics - The lakes investigated in this study (n = 606) were selected based on the availability of satellite-derived LSWT observations (see below). The study sites vary in their geographic and morphological characteristics. They range in altitude between -216 m above sea level and 4,753 m above sea level, in latitude between 54.55 °S and 74.48 °N, in surface area between 49.06 km^2 and 81,844 km^2, and in mean depth between 0.1 m and 738.7 m (Table S1).

2.2. The air2water model - To simulate LSWT in each lake, we used the *air2water* model (Piccolroaz et al. 2013), an open-source model that simulates LSWT relying solely on surface air temperature observations as reasonable proxy for the overall external forcing. It is a zero-dimensional heat budget model to the well-mixed surface volume of the lake, accounting for all the heat flux components at the lake-atmosphere interface (shortwave radiation, longwave radiation, and diffusive terms) mathematically simplified to obtain a simple ordinary differential equation. The added value of *air2water* compared to purely regressive models is the explicit inclusion of the effect of vertical thermal stratification on lake thermal dynamics through a simple, yet effective, empirical relationship. In this respect, the model showed good ability also to simulate the seasonal evolution of the well-mixed layer thickness (Toffolon et al. 2014; Piccolroaz et al. 2015). A detailed description of the model is available in Text S1 in the Supplementary material.

The six model parameters of *air2water* (see Text S1) were calibrated by optimizing a metric of model performance via an automatic optimization procedure (Particle Swarm Optimization, Kennedy and Eberhart 1995), using only air temperature as input and observed LSWT as reference. In this way, the model is data-driven (Solomatine et al. 2009), while being physically based, allowing for distilling information about the behaviour of the system into the values of the parameters. The model equation was solved numerically by using the Crank-Nicolson numerical scheme with a daily time step.

2.3. Surface air temperature - We downloaded the air temperatures needed to drive *air2water* from the European Centre for Medium Range Weather Forecasts' (ECMWF) ERA-20C reanalysis product, which provides air temperature at 2-m height above surface at a daily time step and at a grid resolution of 1° (European Centre for Medium-Range Weather Forecasts, 2014). Time series data were extracted for the grid point situated closest to the centre of each lake, defined as the location of maximum distance to land, calculated using the distance-to-land dataset of Carrea et al. (2015). When the surface elevation of the ERA-20C grid was not equivalent to the elevation of the lake, surface air temperature was corrected to over-lake values using appropriate lapse rates (Γ). Γ is variable within short time periods (Rolland 2003), due to, among other things, synoptic circulations (Pagès and Miró 2010) and changing cloud cover (Minder et al. 2010), and therefore in this study we followed the method of Gao et al. (2012). We evaluated site-specific Γ by calculating the difference between temperatures at two pressure levels covering the maximum elevation range of a grid (such as 850 hPa and 925 hPa) and divided through the differences in the corresponding geopotential heights (i.e., the geopotential $m^2\ s^{-2}$ divided by the gravitational acceleration $9.81\ m\ s^{-2}$).

2.4. Satellite-derived lake surface temperature data – The parameters of the *air2water* model were calibrated against satellite-derived lake surface water temperature data from the ARC-Lake v3 dataset (MacCallum and Merchant 2012), available at http://www.laketemp.net. Daily lake-mean time-series were obtained from the spatially-resolved satellite data by averaging across the lake area. Lake-mean surface temperatures were used in order to average across the intra-lake heterogeneity of LSWT responses to climate change (Woolway and Merchant 2018; Zhong et al. 2018). We used fifteen years (1996-2010) of data to calibrate the model. Such a calibration period was shown by Piccolroaz (2016) and Piccolroaz et al. (2018) to be sufficient to generate accurate predictions of LSWT using *air2water*, also when the time series is affected by large gaps (as is common in satellite-derived lake surface temperature due to the presence of clouds). The entire satellite-data period was used to make the derived model parameters as robust as possible.

2.5. Statistical methods and analysis – The accuracy of *air2water* in simulating LSWT was evaluated by calculating the Root Mean Square Error (also used as performance metric for model calibration):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\hat{T}_{w,i} - T_{w,i}\right)}{N}}, \qquad (4)$$

and the Nash Sutcliffe Efficiency Index (Nash and Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(\hat{T}_{w,i} - T_{w,i}\right)}{\sum_{i=1}^{N}\left(\hat{T}_{w,i} - \bar{T}_{w}\right)}, \qquad (5)$$

where $\hat{T}_{w,i}$ and $T_{w,i}$ are the daily observed and simulated LSWT at time i, $\bar{T}_w$ is the mean of observed temperature, and N is the length of the observational record. The NSE is a normalized metric that provides an evaluation of model performance relative to the variability of the observed time series. This metric ranges from $-\infty$ to 1: a value of 1 corresponds to a perfect match between measured and simulated values, and a value of 0 indicates that the model prediction is as accurate as using the mean of the observations. In this study, we define the lakes that are reasonably well modelled by *air2water* as those with a NSE of greater than 0.8.

The statistical metrics above were compared across climatic zones, as identified by the Köppen climate classification (Köppen and Geiger 1930; Köppen 1990), which provides an efficient way to describe climatic conditions defined by multiple variables and their seasonalities. Here, we used the Köppen climate classification for a long-term average climate (1901-2010), using the same criteria as Kottek et al. (2006) and Chen and Chen (2013). The Köppen classification uses monthly temperature and precipitation data averaged over the 1901-2010 period, on a 0.5° longitude x 0.5° latitude grid. For a fuller account, refer to Chen and Chen (2013). The Köppen climate classification of each lake is given in Table S1. The main characteristics of the Köppen climate zones are described in Table S2.

The long-term variations of air temperature and LSWT were analysed in terms of annually-averaged temperature anomalies relative to the reference period 1951-1980. For each lake, thermal reactivity to changes in air temperature was quantified as the slope of the regression line (without intercept) between annually-averaged air temperature anomalies (x-axis) and LSWT anomalies (y-axis) over the 1900 to 2010 period (excluding the reference period 1951-1980).

3. Results

3.1. Model performance – The results of using *air2water* to simulate the seasonal cycle of LSWT is illustrated in Figure 1. We compared the time series of observed and simulated LSWT for five selected case-study lakes (Lake Malombe, Lake Assad, Lake Garda, Lake Tahoe, Har-Hu Lake), one from each of the major Köppen climate classification zones. The calculated daily RMSE of each case-study lake was below 1 °C, and the NSE was above 0.9. Inspection of these time series suggests that the model is able to capture several aspects of the inter-annual variability in LSWT, such as the timing of warming and cooling, and year-to-year differences in the summer maximum and winter minimum. In addition, *air2water* is able to simulate the presence and timing of ice cover (where applicable) and the annual range in LSWT (Fig. S1).

To extend the evaluation of the ability of *air2water* to simulate LSWT worldwide we show, in Figure 2, the calculated daily RMSE and NSE for all lakes, inherently characterized by considerably different annual LSWT cycles (see Fig. S2). The calculated RMSE between modelled and observed daily LSWTs across the study sites varied between 0.41 °C and 2.32 °C, with an average value among all the lakes equal to 1.10 °C. The RMSE values were less than or equal to 1.00 °C in 38% of the lakes studied, and less than or equal to 1.50 °C in 91% of cases. The computed NSE also varied among lakes, ranging between -0.05 and 0.99, with an average value among all the lakes of 0.90. A NSE larger than 0.95 was calculated in 74% of lakes, while a value larger than 0.90 was calculated in 84% of lakes. Cases of NSE close to 0 were restricted to equatorial lakes, while it rapidly increased to a value close to 1 towards approximately 15° latitude (North and South, Figs 2b and d). As further commented in the Discussion, such low values of this performance metric were primarily linked with the thermal characteristics inherent to these lakes, which are characterized by small variance of observations (see Fig. S2b), rather than with substantial model deficiencies. This is also suggested by the absence of any strong relationship between latitude and the calculated RMSE, which shows relatively small values throughout the range of considered latitudes (Fig. 2c), except for a slight decrease in model performance at higher latitude, in particular northward of 50°N.

Although latitude can be assumed as a first proxy for mean climatic conditions, we reinforced this analysis by evaluating the two metrics of model performance among the more representative Köppen climate classification zones (Fig. 3). The RMSE in lakes situated within a 'Tropical' climate was 0.87 °C (n = 80), compared to 1.08 °C (n = 51) in lakes situated within a 'Dry' climate, 1.02 °C (n = 143) in lakes situated within a 'Mild temperate' climate, 1.21 °C (n = 313) in lakes situated within a 'Snow' climate, and 1.05 °C (n = 19) in lakes situated within a 'Polar' climate. The RMSE was comparable among the five climatic zones, although slightly smaller values were obtained for 'Tropical' and 'Polar' regions. Conversely, the comparison of the calculated NSE among the Köppen climate classification zones demonstrate clearly that, relative to this metric, model performance was lower in tropical lakes, compared to any other climate zone. In particular, we calculated an average NSE of: Tropical = 0.55, Dry = 0.95, Mild temperate = 0.94, Snow = 0.96, Polar = 0.92. However, some lakes situated within the 'Mild Temperate' (n = 7) and 'Dry' (n = 1) Köppen climate zones also experienced poor model fit (NSE<0.5), but these were situated at low latitude. Specifically, these lakes were clustered in Central-Eastern Africa (Fig. 2b), essentially in a 'Mild Temperate' Köppen climate zone of the type *Cfb*, a subtropical oceanic climate that can be found in mountainous locations of some tropical countries (Fig. 3b).

3.2. Global 20th century temperature evolution- Figure 4a and b show the modelled LSWT variations (annually-averaged temperature anomalies) of the studied lakes along with the corresponding air temperatures variations, grouped by Köppen climate zones and separated between Northern and Southern Hemisphere, from 1900-2010. The analysis was carried out only on lakes with a NSE higher than 0.8 (n = 540). The results indicate that lake surface temperatures have varied considerably from 1900 to 2010, with substantial differences between lakes in the Northern (n = 479) and Southern Hemisphere (n = 61) and across Köppen climate zones. For example, while in both Hemispheres a clear warming occurred since the 1980s, different trends emerged during the first half of the century (e.g., prior to 1950). A previous pronounced warming period, during the so called Early Twentieth Century Warming (ETCW) (see e.g., Hegerl et al. 2018), involved all but Tropical lakes in the Northern Hemisphere and particularly lakes in the 'Snow' Köppen climate zone (see also the Discussion for further details). On the contrary, lakes in the Southern Hemisphere were characterized by slower but continuous warming after the 1920s. A synthesis of the warming trends in the two hemispheres and across Köppen climate zones is provided in the Supplementary material (Table S3) for overlapping subperiods of 30 years.

Such distinct LSWT dynamics clearly reflect different air temperature trends, but LSWTs were substantially modulated by the lakes' thermal reactivity, which is different depending on the Köppen climate zones (Fig. 4c; see also Table S3). In all lakes, the thermal reactivity to changes in air temperature quantified through the regression fit described in Section 2.5 was statistically significant ($p < 0.01$). Results are summarized in Figure 4c, grouped by climate zones. On average the annually-averaged thermal reactivity, was higher (i.e., more responsive lakes) for the 'Mild Temperate' zone (median value of 0.55), and lower (i.e., more resilient lakes) for the 'Snow' and 'Polar' zones (median value of 0.17 and 0.18, respectively; see also Fig. S3). Lakes in the 'Tropical' and 'Dry' climate regions had intermediate values (median value of 0.48 and 0.36, respectively). The effects on LSWT response to air temperature trends are clear. In the Northern Hemisphere, after the 1990s air temperature in the 'Polar' and 'Snow' regions warmed more than in the other climate regions, but LSWT did not respond considerably as an annual average. Conversely, lakes in the 'Mild Temperate' region experienced a significant warming, almost four times more intense than in the 'Polar' and 'Snow' regions (on average 0.48°C *vs.* 0.12°C, relative to the reference period 1951-1980; see also Table S3 for an overview of the different air temperature and LSWT warming trends across Köppen climate zones).

The low thermal reactivity observed in lakes that freeze in winter (particularly in the 'Polar' and 'Snow' regions) are, at least partially, ascribable to the insulating effect of the ice-cover, which inhibits heat exchange at the lake-atmosphere interface. As expected, the same slope of the regression line between annually-averaged air temperature anomalies and LSWT anomalies evaluated considering only the ice-free period indicated clearly higher thermal reactivity in all but 'Tropical' lakes (since these lakes do not freeze), and particularly in lakes located in the 'Snow' and 'Polar' regions (Fig. S4). This is coherent with previous studies that suggested that deep and cold lakes exhibit an amplified response of LSWT to changes in air temperature in summer (Piccolroaz et al. 2015; Zhong et al. 2016; Woolway and Merchant 2017). Despite this amplification effect expected for deep lakes in the 'Snow', 'Polar' and cold 'Dry' regions, however, on an annual basis the lakes located in the 'Mild Temperate' region are confirmed to be the most thermally responsive.

4. Discussion

Many earlier studies have used models to simulate LSWT change, but these have typically focused on individual lakes (Hadley et al. 2014; Piccolroaz et al. 2018), or a large number of lakes within a confined region (Hondzo and Stefan 1993; Read et al. 2014; Winslow et al. 2017a; Woolway et al. 2017a; Czernecki and Ptak 2018; Prats and Danis 2019). In addition, a large proportion of previous studies have used models that require a number of meteorological variables. Prior to this investigation, no known studies have simulated LSWT responses to climate change in lakes worldwide by using surface air temperature as the only climatic driver.

For many of the 606 studied lakes, *air2water* was able to predict accurately LSWT during the satellite-period. One of the most relevant features of the *air2water* simulations was that the model was able to reproduce accurately inter-annual fluctuations of LSWT. This is particularly remarkable considering that air temperature from reanalysis at grid resolution of 1º was used in the model calibration. The *air2water* model performed best, as evaluated by NSE, in non-tropical lakes. In general, a decrease in model performance can be observed towards the equator. However, we must note that this is predominantly a result of the minimal seasonal variability of LSWT in these lakes and is inherent in the definition of NSE. Specifically, lakes at low latitudes (i.e., lower than 15° North and South) typically experience a seasonal range of < 5 ºC compared to > 25 ºC in some temperate lakes (Fig. S2). Thus, the same RMSE between observed and modelled LSWT has a greater impact on model accuracy, in terms of NSE, in near-equatorial lakes. However, we notice that the worst model performance was bounded between 15 °S and 15 °N, while in the remainder of the tropical region it was comparable to that of lakes located in the other climatic regions. In this regard, among the 66 lakes excluded from the analysis because associated to NSE values lower than 0.8, the 92% was between 15 °S and 15 °N and the 83% belonged to the 'Tropical' region.

Besides the clear predictive value of this simple tool, *air2water* has also some limitations. Surface air temperature is closely related to some of the heat fluxes controlling the net surface energy budget in lakes, such as surface radiation, which is typically a dominant heating term at the lake surface (Schmid and Köster 2016). This allows LSWT to be modelled as a function of air temperature alone in some lakes (Livingstone and Lotter 1998). However, other variables such as humidity and wind speed, can influence greatly the lake surface energy budget and thus LSWT (Edinger et al. 1968). For example, tropical lakes experience higher latent heat loss, compared to lakes situated in other climate zones, as a result of the Clausius-Clapeyron relationship whereby the air-water humidity difference, to which the latent heat flux is proportional, increases with decreasing latitude (Woolway et al. 2018). In addition, abundant precipitation can contribute to the heat budget of these lakes (Rooney et al. 2018), and the atmospheric boundary layer is typically unstable (Woolway et al. 2017b) resulting in enhancement of near-surface wind speed and greater turbulent heat loss. Some of these contributions are, at least partially, accounted for in the seasonal term included in the *air2water* model, although they do not explicitly appear in the model equations (see Text S1 and Fig. S6 in the Supplementary material)

Modelled LSWT also demonstrate a slight decrease of model performance towards higher latitude, in particular in lakes situated in northern Siberia and northern North America. This could indeed be an artefact in the LSWT data used in the model calibration, such that these lakes are typically ice-covered for a large part of the year, thus reducing the number of observational points available for calibration. Additionally, a physically-based ice module has not yet been implemented in the *air2water* model, possibly affecting its performance when applied to lakes that freeze in winter, although the current version of the model has showed good performance also in these cases (Toffolon et al. 2014; Piccolroaz et al. 2015; Czernecki and Ptak 2018; Piccolroaz and Toffolon 2018). Finally, we should notice that also hydrological (e.g., groundwater and snow-melting inflows) and anthropogenic (e.g., sewage inflows, cooling/heating systems) factors may affect model performance in some lakes, which are only implicitly included in the formulation of the model.

Given the relatively short duration of the satellite-period, independent model validation was renounced in favour of a more robust calibration of parameters (model validity has been widely demonstrated in several previous applications). This allowed us to reconstruct the global 20th century LSWT evolution with a certain degree of confidence for the first time, contributing to improved understanding of recent and past evolution of lake thermal dynamics worldwide. The LSWT hindcast period covered also the ETCW pronounced warming period, which mainly involved lakes in the Northern Hemisphere (Fig. 4a). The ETCW period has been attributed to a combination of external forcing and internal decadal variability, and it is visible also in other global temperature datasets such as HadCRUT4 (see e.g., Hegerl et al. 2018). It was particularly prominent over high latitudes of the Northern Hemisphere, and encompassed exceptional events as for example the Greenland warming in the 1920s-1930s (Chylek et al. 2006) and the 'Dust Bowl' drought and heat waves in North America in the 1930s (Cowan et al. 2017). The effects on LSWT are appreciable from some of the few long-term time series covering this period (Magee and Wu, 2017; Potemkina et al. 2017), although due to data scarcity they received little attention. The results presented here provide first evidence and quantification of a systematic warming of high latitude lakes in the Northern Hemisphere during the ETCW, which for lakes in the 'Snow' climate region was more than twice the recent warming (anomalies relative to the reference period 1951-1980 of 0.31°C in the 1920-1940 *vs.* 0.12°C in the 1990-2010). We stress that the magnitude of such warming is inherently dependent on the accuracy of the reanalysis product used in the analysis, which, despite the well-recognized good reliability of the ERA-20C dataset, may further improve in the future. In this regard, we should notice that the ERA-20C dataset is affected by changes in the observing system, especially in regions of sparse coverage as for example the Southern Hemisphere or during periods such as around World War II due to non-standard observing practice during wartime (Poli et al., 2016).

The present analysis focused on annually-averaged temperatures, offering a change of paradigm compared to the recent tendency towards focusing on long-term changes in summer LSWT (Schneider and Hook 2010; O'Reilly et al. 2015; Sharma et al. 2015). Although summer-averaged LSWT have undoubtedly been pivotal in our understanding and for evaluating the direction of warming globally, they cannot be assumed as representative of the overall thermal response of lakes, due to the existence of substantial seasonal variations in LSWT warming rates (Winslow et al. 2017b; Woolway et al. 2017a; Toffolon et al., 2020) primarily modulated by stratification dynamics (Piccolroaz et al. 2015; Zhong et al. 2016). Specifically, lakes thermal reactivity to changes in air temperature is much higher in summer due to strong thermal stratification, thus lower thermal inertia (Piccolroaz et al. 2015). This is exemplified by the larger values of the thermal reactivity illustrated by Schmid et al. (2014) considering equilibrium LSWT (a proxy for summer lake temperature), compared to our results based on annual averages (Figure 4c).

Analysing annual averages in this study allowed us to obtain an integrated overview of lakes thermal dynamics overcoming the seasonal-specific validity of previous global trends. We claim that this is a first step towards extending our understanding of lakes thermal behaviours to all seasons. In fact, not only the intensity but also the timing of air temperature variations crucially affects the extent to which lake surface temperature changes (Piccolroaz et al. 2015; Zhong et al. 2016). In this regard, we note that the lakes thermal sensitivity evaluated in this analysis (Fig. 4c) should be intended as an average value for the study period, while locally it may undergo changes depending on specific air temperature variations throughout the season, possibly modulated also by the insulating effect of the ice cover in lakes that freeze in winter. In addition, morphological factors such as mean depth are known to affect lakes thermal inertia (Toffolon et al. 2014), explaining part of the variability of the computed lakes thermal sensitivity within the same climatic group (Fig. 4c). However, this did not prevent from identifying marked differences across the climatic zones (Fig. S5), with lakes in the 'Mild Temperate' region being the most responsive to air temperature changes, but adds another element to be carefully considered in future analyses.

5. Conclusions

In this study we presented the first reconstruction of the global 20th century LSWT evolution and contributed to improved understanding of the impact of climate change on lake thermal dynamics worldwide. To this end, we used a simple, but mechanistically based model, *air2water*, which relies on air temperature as the only climate input. In terms of RMSE between observed and modelled daily temperatures, *air2water* was able to simulate the surface temperature of many lakes to within 1.5 ºC, similar to the performance achieved by other, more computationally expensive models, which require additional meteorological input data (Stefan et al. 1998; Peeters et al. 2002; Thiery et al. 2014; Zhong et al. 2016; Prats and Danis 2019).

The results illustrated highly variable LSWT trends during the 20th century and across climatic regions, with lakes located in the temperate regions being the most thermally responsive. Substantial warming was evident after ~1980 in both hemispheres, while a previous pronounced warming period was found in the Northern Hemisphere providing first evidence of a systematic warming of high latitude lakes during the so called Early Twentieth Century Warming period (1920-1940).

The modelled annually-averaged LSWT and the corresponding air temperature data are made available in the Supplementary material for all lakes (limited to lakes with NSE>0.8; Tables S4 and S5), along with their linear trends calculated separately for the Northern and Southern Hemispheres and for the Köppen climate major groups for overlapping subperiods of 30 years (Table S3). The aim is to offer a global 20th century baseline, against which observed and projected lake warming and future applications based on new reanalysis products can be referenced.

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Figures Legends

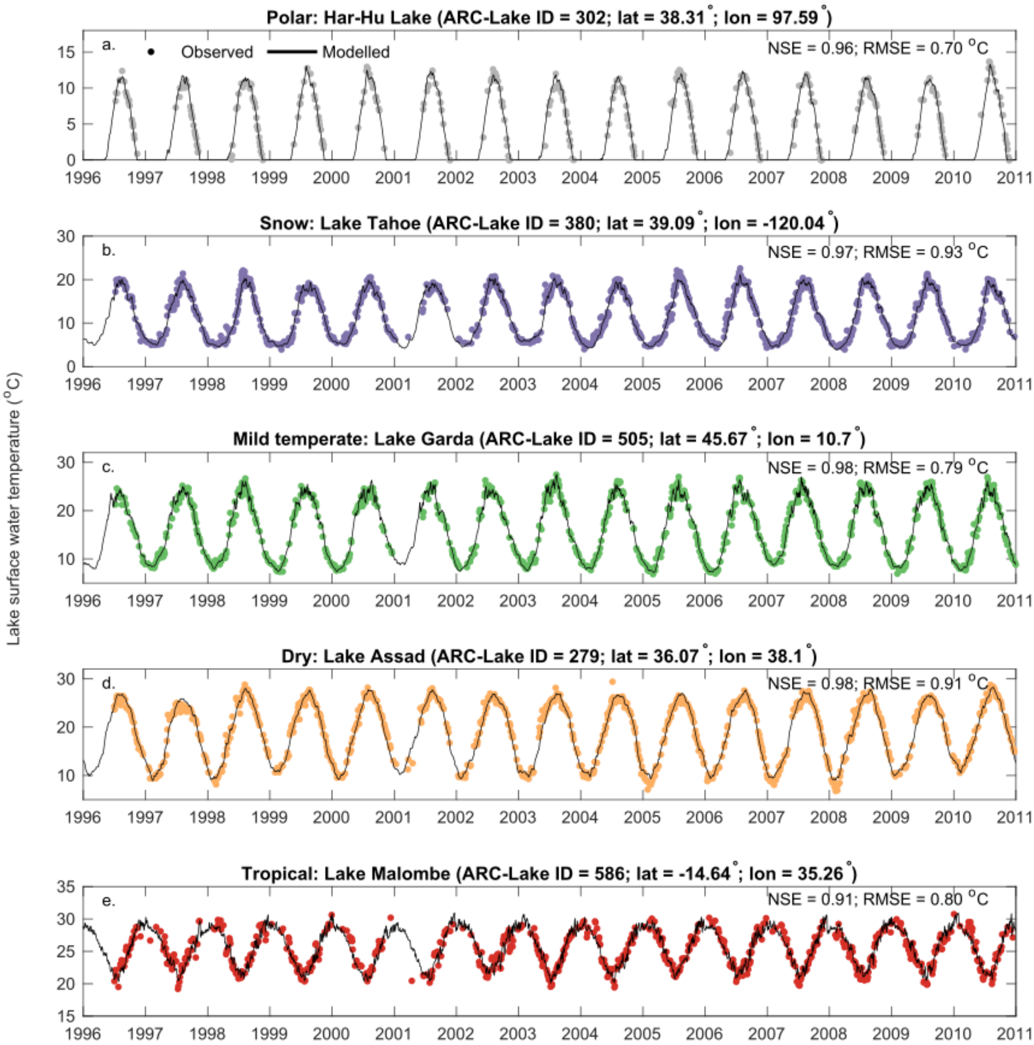

Figure 1. Comparison of modelled (solid line) lake surface water temperatures with satellite-derived (points) temperature observations for (a) Har-Hu Lake (China), (b) Lake Tahoe (United States), (c) Lake Garda (Italy), (d) Lake Assad (Syria), (e) Lake Malombe (Malawi). Shown are the calculated NSE and RMSE between the observed and simulated daily LSWT.

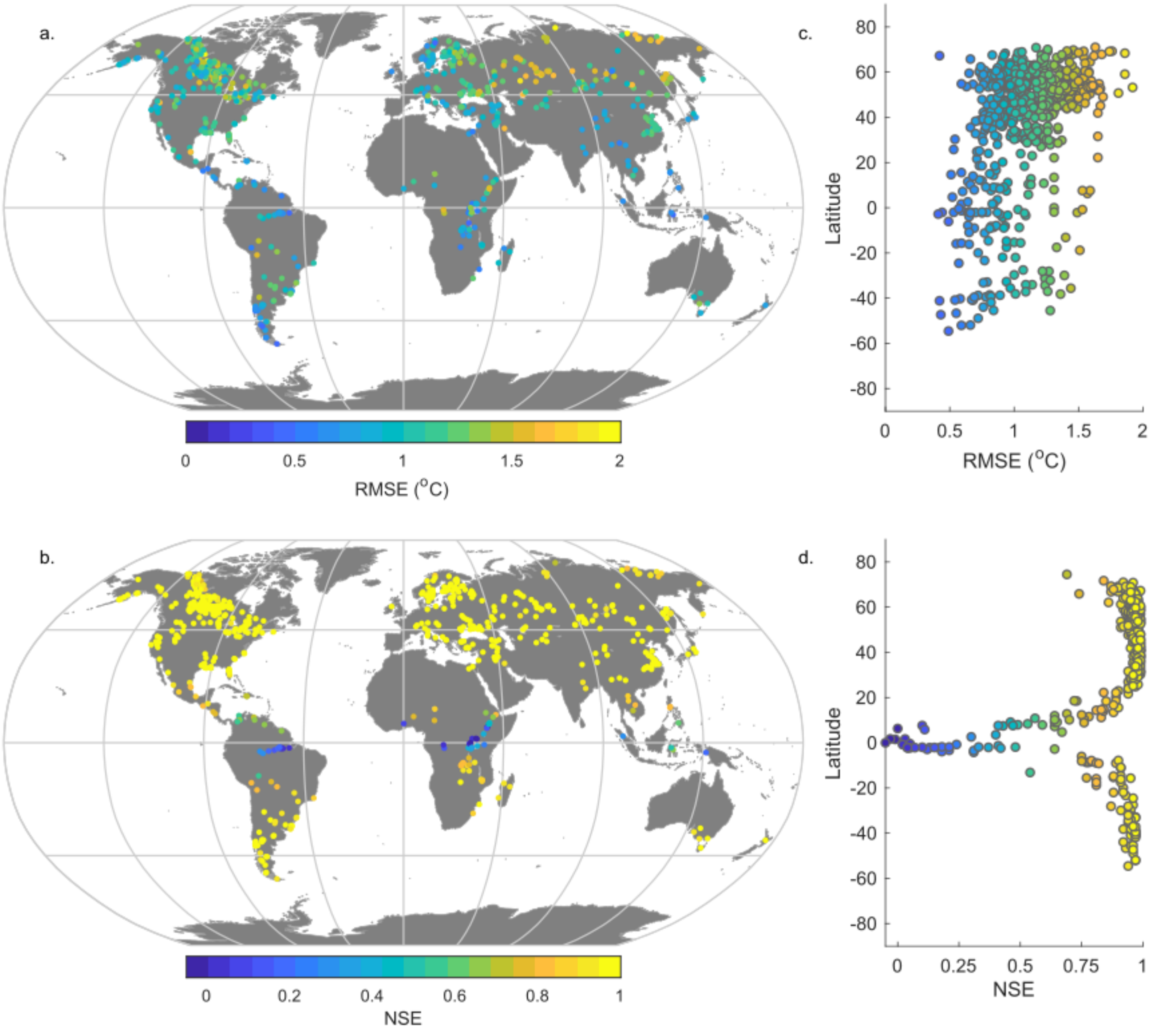

Figure 2. Global patterns in the computed performance of *air2water*, evaluated via (a) RMSE and (b) NSE between the observed and simulated daily LSWT. The relationship between latitude and (c) RMSE and (d) NSE are also shown.

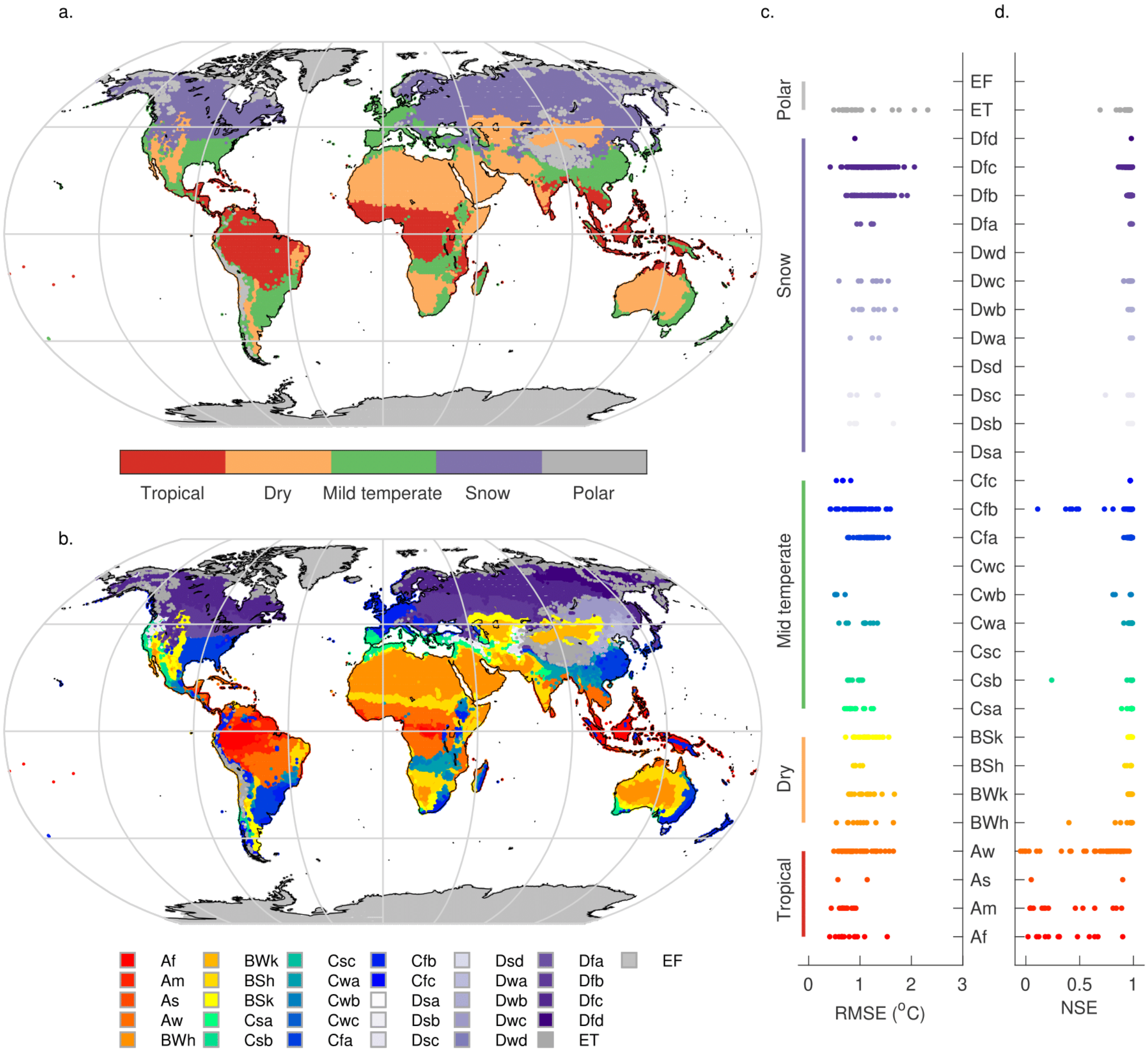

Figure 3. Relationship between the performance of *air2water* and the Köppen climate classification, showing both (a) the major climate types and (b) the climate sub-types. Model performance is evaluated by (c) RMSE and (d) NSE between the observed and simulated daily LSWT.

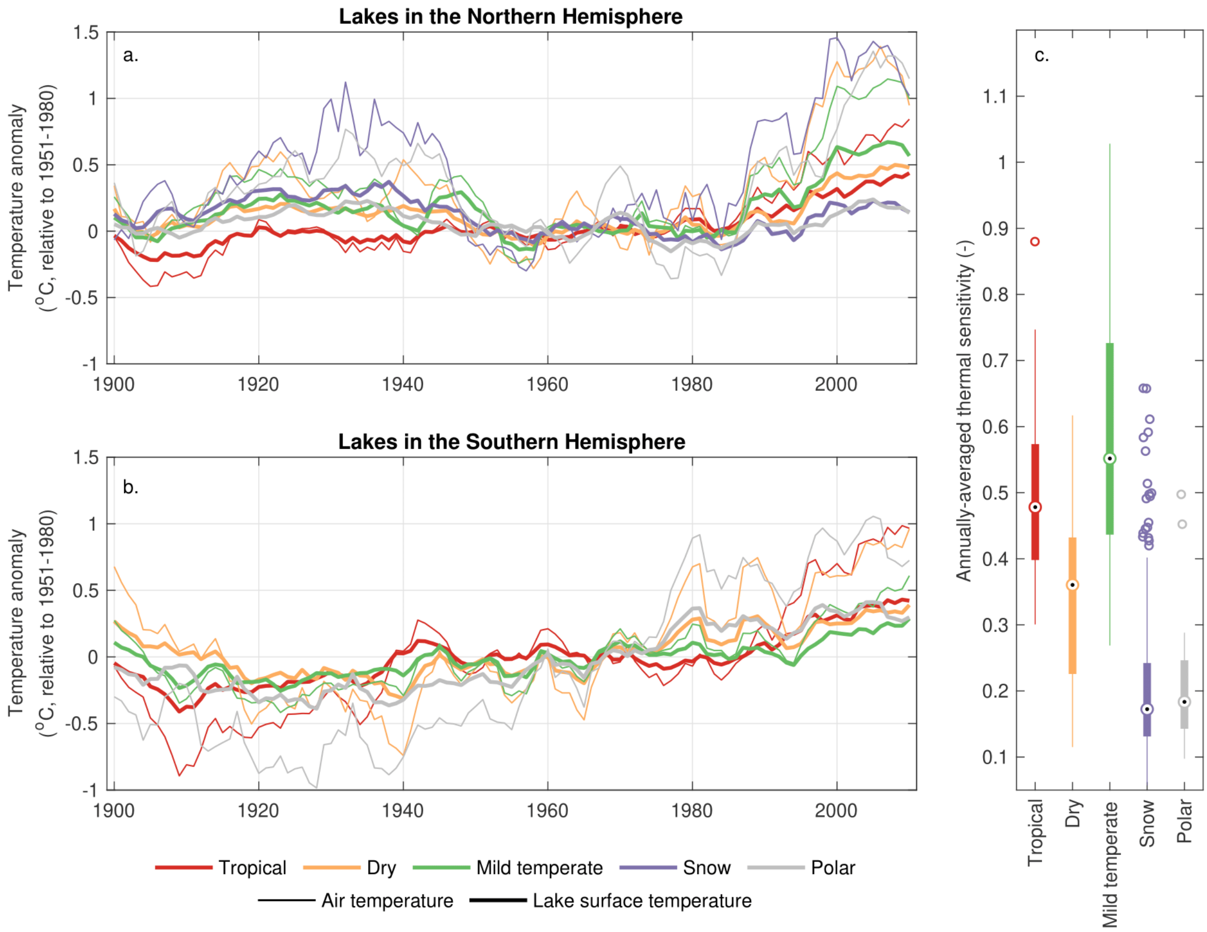

Figure 4. Long-term LSWT variations for each major Köppen climate zone for the period 1900-2010 shown for (a) lakes in the Northern Hemisphere and (b) lakes in the Southern Hemisphere. Only lakes with a NSE higher than 0.8 were included in this long-term analysis. A five-year moving average is applied to the lake and air temperature data. Also shown is lakes thermal sensitivity, defined as the slopes of the regression line between annually-averaged air temperature anomalies and LSWT anomalies over the 1900 to 2010 period, grouped by climatic region (c).